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Helical Probe Tests for Shallow Soil Exploration

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Paul W. Mayne
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January 1986

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Washington, DC 20314-2300
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Helical test probes of different sizes,suitable for in situ soil exploration to a shallow (1.8m) depth and compaction control were developed and tested in different soils alongside traditional in situ tests, including Standard Penetration tests (SPT), cone penetration tests (CPT), dilatometer tests (DMT), and in situ density tests. The helical probe test (HPT) is economical and can be performed by a single person. The torque necessary to insert the probe is used as a measure of soil characteristics. It was found that: the HPT test correlates well with the SPT test and the correlation is not sensitive to the soil type (particle size); the HPT test correlates well with the CPT test, but the correlation is sensitive to the soil type; the HPT/SPT and HPT/CPT correlations are consistent with existing data on SPT/CPT correlations; The HPT torque provides a sensitive measure of relative compaction and in situ dry density of compacted soils.

Key Words: construction supervision; field test equipment; helical augers; in situ measurements; penetration tests; residual soils; soil investigation; soil mechanics; test procedure.

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LIST OF SYMBOLS

D_{50} Particle diameter below which 50 percent of the soil by weight is finer, in mm

D_f Force required to advance the Marchetti dilatometer in the soil in kN

E Young's Modulus in MPa

$E_D = E/(1-\nu^2)$ Dilatometer modulus in MPa

n Number of data points

N Blow count in Standard Penetration Test in blows per ft (0.305m)

q_c Tip resistance in CPT test in kPa x 10^{-2} (bars or tsf)

$R = t_i/t_{12}$ Ratio of the torque of a probe of type "i" to the torque of the Y12 probe

$RC = [(\gamma_d(field)/(\gamma_{dmax}$ (ASTM D698)]x100 relative compaction in percent

s Standard deviation of sample in units of sample

s^2 Variance of sample in (unit of sample)^2

t_i Torque of a helical probe of type "i" in inch-lb

TR Ratio of reverse torque to torque requird to advance the probe in percent

v_s Shear wave velocity in m/s

γ_d Dry density of soil in Mg/m^3

ν Poisson's Ratio

SUBSCRIPTS USED

ABC	A.B. Chance probe
8	Y8 probe, 1/2 inch (12.7 mm) O.D.
12	Y12 probe, 3/4 inch (19.1 mm) O.D.
16	Y16 probe, 1 inch (25.4 mm) O.D.
24	Y24 probe, 1- 1/2 inch (38.1 mm) O.D.
max	Maximum

ACRONYMS USED

CPT	Cone penetration test
DMT	Marchetti Dilatometer Test
HPT	Helical Probe (NBS) test
NBS	National Bureau of Standards
SPT	Standard Penetration Test

1. INTRODUCTION

It is frequently required to determine the in situ strength and density characteristics of soils at a shallow depth. The authors developed and tested helical probes which can be screwed into the soil to a depth of 1.8 m. The magnitude of the torque required to insert the helix is used as a measure of soil resistance. The probe can be operated with ease by one man. It could also be coupled with drillrods and used at a greater depth with proper provisions for the transfer of torque.

Within its range of applicability (soils with no large rock fragments which could inhibit penetration) the helical probe test is more economical than traditional exploration methods, and in accordance with the data obtained to date, yields results of comparable quality.

A similar probe was developed by the anchor industry and used to predict the pullout strength of shallow soil anchors. The results of a limited National Bureau of Standards (NBS) study of that latter probe [14], which was marketed by the A.B.Chance[1] Company as the "soil test probe", indicated that the torque readings correlate well with the in situ shear strength of the soil. This observation prompted NBS to initiate a further study of the concept of using helical probes for in situ measurements. In particular, it was considered desirable to develop a probe which requires less torque to operate and has better penetrating capabilities than the A.B.Chance probe. The results of this study are reported herein.

In the report the results of helical probe tests are compared with those obtained by commonly used soil exploration tests: the Standard Penetration test (SPT), the cone penetration test (CPT),

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1. References to commercial products do not constitute endorsement by tthe National Bureau of Standards.

the flat plate dilatometer test (DMT), and the Standard Proctor compaction test linked with in-place density tests.

The Standard Penetration (SPT) test (ASTM D1586-84 [5]) was developed in 1927 and is the most widely used soil exploration test in U.S. and worldwide geotechnical engineering practice. The test is performed by dropping a 63.5 kg hammer from a height of 0.76m to drive a drillrod with a standard split-tube sampler into the ground. The number of blows necessary to achieve a 1-ft (0.3m) sampler penetration,"N", is used as a measure of soil resistance. The test has been empirically correlated with many soil characteristics, including allowable bearing capacity of foundations, in situ shear strength, density, stiffness and compressibility, and liquefaction potential during earthquakes.

The cone pentration (CPT) test (ASTM D3441-75T [7]) is widely used in European practice and is gaining increasing popularity in the U.S. The test is performed by pushing a cylinder with a conical tip into the ground. The cylinder has a 1000 mm^2 cross sectional area and a 15000 mm^2 surface area and the conical tip has a 60 degree apex angle. Soil resistance is measured by the resistance to the penetration of the conical tip and the frictional forces exerted on the side of the cylinder which are measured separately. The CPT has been empirically and theoretically correlated with the bearing capacity of deep and shallow foundations, and with the shear strength, density, stiffness and compressibility of soils.

The flat plate dilatometer (DMT) (Marchetti, 1980 [9]) consists of a 95mm wide by 200 mm long by 14 mm thick pointed flat plate with a 60 mm diameter thin circular expandable steel membrane at its center. The plate is pushed into the ground and the membrane is inflated by pressurized gas. The soil resistance to the membrane expansion is used as a measure of soil characteristics. The test is of recent origin and is primarily used to measure

soil stiffness and in situ confining pressures.

Compaction tests (ASTM D698-78 [4]) are designed to measure the moisture-density characteristics of soils. Soil samples are compacted in a standard mold with a standard rammer dropped from a prescribed height a prescribed number of times on three successive layers of soil within the mold, to determine the densest state to which the soil can be compacted by the prescribed method. This maximum density is then compared with the in-place density of the compacted soil at the construction site to determine relative compaction in the field. The referenced test, as well as a modified version which uses higher compaction energy are the most widely used methods for obtaining reference densities when monitoring the in-place density of compacted soils.

Once reliable correlations between the helical probe test and the above described tests are established, it will be possible to use the helical probe test in many phases of geotechnical engineering practice.

2. TEST PROBES AND PROCEDURES USED

Figure 1 shows the four test probes developed by NBS. The probes consist of a helical screw connected to a 5-1/2 to 6 ft (1.7 - 1.8 m) long shaft. At the upper end of the shaft is a hexagonal nut for applying the torque. Figure 2 shows a helical probe (HPT) test in progress. The probe is inserted into the ground by turning it in a clockwise direction. No vertical force needs to be applied. A torquemeter with a dial gage is used to read the torque needed to insert the probe. Figure 3 shows a test probe with the attached torquemeter. Torque readings are generally taken at 6 in (15 cm) penetration intervals,however it is also possible to monitor the torque continuously. The rate of advance during a torque reading is kept to approximately 4s for a 180 degree turn. Average rather than peak torque is recorded[2]. After completing the test the probe is withdrawn by turning it in the counter clockwise direction. For some of the tests the torque needed to withdraw the probe was also recorded.

Figure 4 shows the different helixes used in the test program. The dimensions of the helixes, going from left to right in Figure 4 are given in Table 1. The long helix on the left in Figure 4 is the A.B. Chance (ABC) probe. All the other probes were developed by NBS.

Other helix configurations were also tried in the test program. Figure 5 shows some double twist helixes which were tried. While these helixes had excellent penetrating characteristics and provided measurements which correlated well with the ABC probe, they were very difficult to extract from the ground and therefore deemed impractical.

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2. Normally the torque tends to remain constant during a 180 degree turn. However occasionally there are "spikes" of high torque when minor obstructions are encountered. These peaks were disregarded.

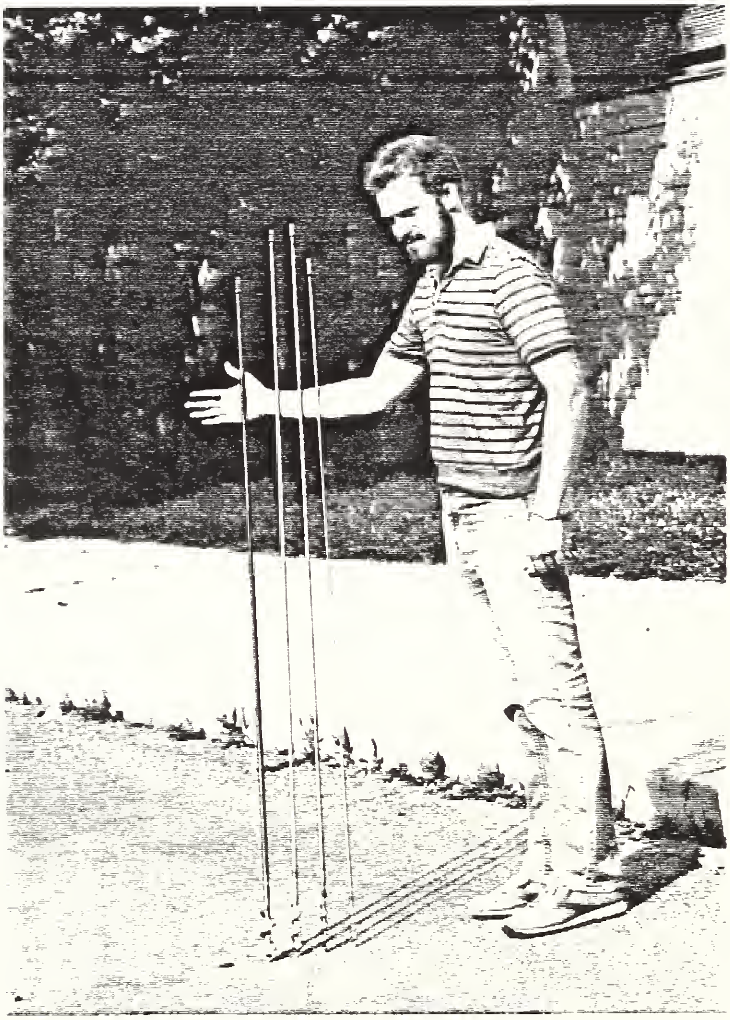

Figure 1. Test Probes Developed by the National Bureau of Standards

Figure 2 HPT Test in Progress

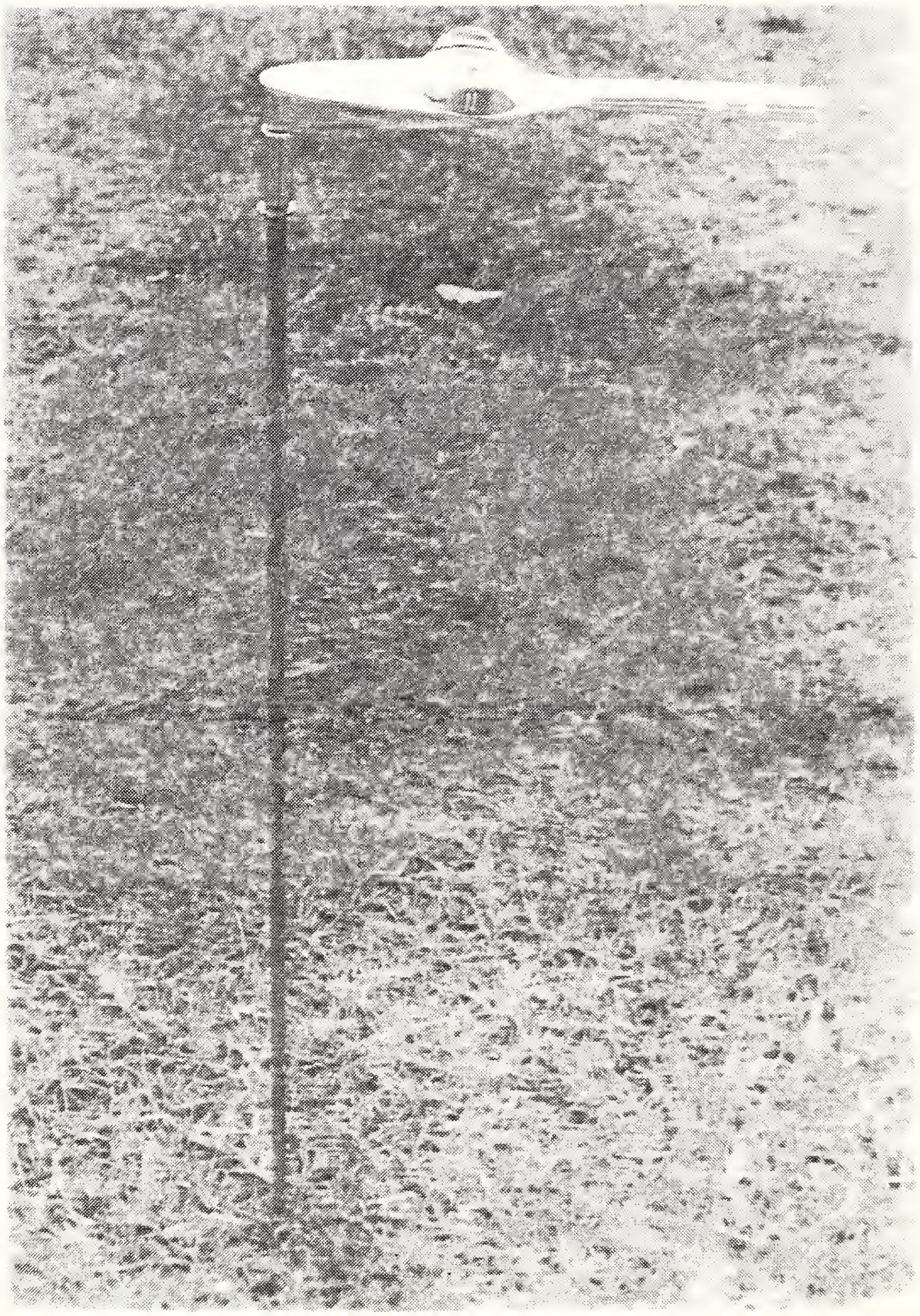

Figure 3 HPT Probe Partially Inserted into the Ground

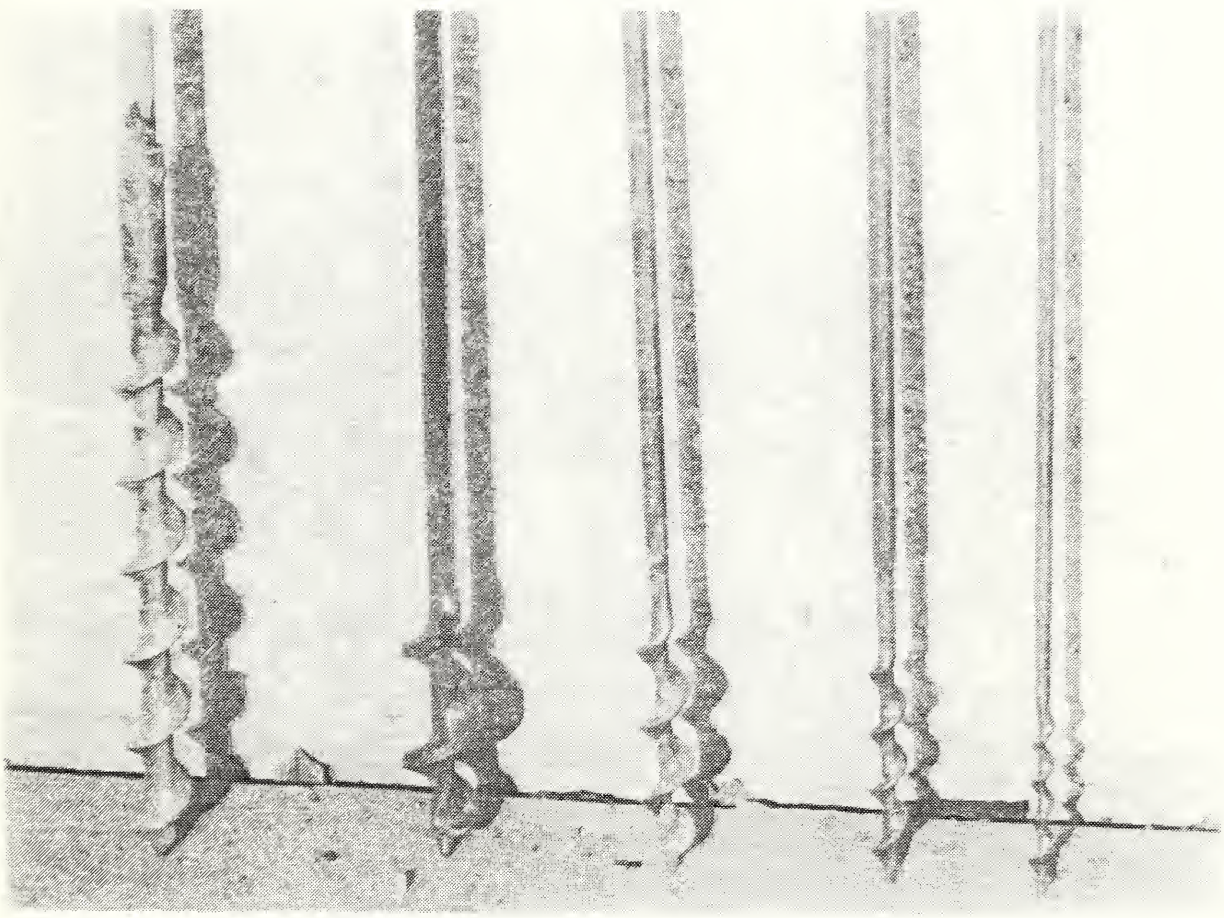

Figure 4 HPT Helixes Used in the Test

TABLE 1. TEST PROBE DIMENSIONS

Probe	Dimensions, inches (mm)				
	Outer Diameter	Lead (Pitch)	Core Diameter	Shaft Diameter*	Length
A.B.C.	1-1/4 (31.8)	1-3/4 (44.5)	9/16 (14.3)	9/16 (14.3)	12 (304.8)
Y24	1-1/2 (38.1)	2-1/8 (54.0)	3/8 (9.5)	1/2 (12.7)	6 (152.4)
Y16	1 (25.4)	1-1/2 (38.1)	5/16 (3.1)	3/8 (9.5)	6 (152.4)
Y12	3/4 (19.1)	1-1/8 (28.6)	1/4 (6.4)	3/8 (9.5)	5 (127)
Y8	1/2 (12.7)	7/8 (22.2)	3/16 (4.8)	5/16 (7.9)	4-1/2 (114.3)

* A 1-1/2 inch (38.1mm) long shaft extension following the probe. The long shaft attached to the probe was generally somewhat more slender.

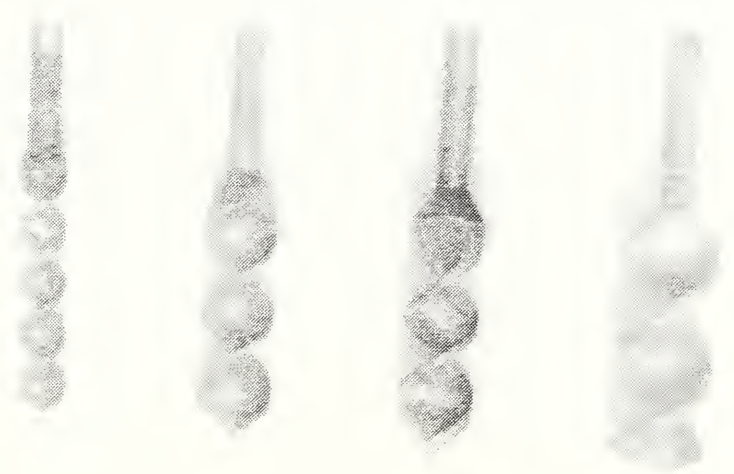

Figure 5 Double Twist Helixes Tried in the Test Program

The special probes developed by NBS (Y24, Y16, Y12 and Y8) were built by modifying standard commercially available wood auger bits. The numbers after the Y designate the outer diameter of these auger bits in multiples of 1/16 inch. Thus, the Y16 probe has a 1 inch (25.4 mm) outer diameter. The probes were built by grinding off the cutting edge of the auger bits and pointing the threads (converting them from square threads to triangular threads). The result is a helical screw which easily penetrates the soil without the aide of a vertical downward thrust and which can be extracted by turning in the opposite direction since it does not shear the soil between the threads. Figure 6 shows a No. 8 wood auger bit alngside a Y8 helical probe. The probe works well in cohesive soils and soils which are not desiccated and in moist sands. Problems arise when the soil between the threads is broken off. This can occur in dry sands and desiccated clays, or when an obstruction is encountered at the tip.

As developmental work with the test probes proceeded it became clear that the Y12 probe is the most practical size for the soils that were tested, which developed torques ranging from 20 to 150 in-lb (1 in-lb 0.113 N-m). For very soft or loose soils the Y24 probe would be more accurate and also more economical (it would penetrate twice as fast). Conversely, the Y8 probe could be used in dense soils. However, because of its small pitch, a test with the Y8 probe is time consuming. Four types of torquemeters were used in the acquisition of the data presented in this report. Most of the data with the Y12 probe were taken with a 150 in-lb torquemeter equipped with a dial gage which is accurate to 2 percent of the applied torque. ABC probe data which were taken simultaneously with Y12 data were measured either with the torquemeter described above, or with a similar 600 in-lb meter which is accurate to 2 percent of the torque or 3 in-lb, whichever is less. Early ABC data which are correlated with CPT readings (footnote 2 in Tables 2 and 3) were taken with an

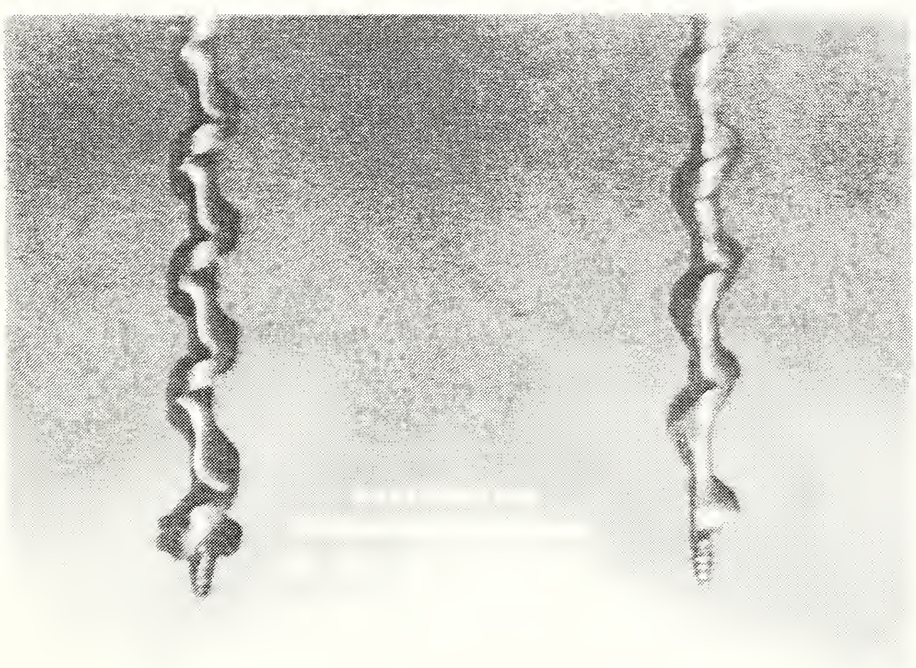

Figure 6 No.8 Wood Auger Bit and Y8 Helical Test Probe

electronic torquemeter which has greater accuracy than the meters described above, but is not very practical for field applications. Torque readings for data which were taken from Reference [13] and are for ABC readings correlated with SPT data (footnote 2 in Tables 2 and 3) were taken with a beam type torque wrench which is graduated to 30 in-lb and can be estimated to 10 in-lb. The accuracy of this latter wrench is not specified by the manufacturer, but it was calibrated against other torquemeters and found to be accurate to about 15 in-lb.

3. TEST RESULTS

The helical probe (HPT) data were taken alongside traditional soil exploration data from Standard Penetration Tests (SPT) (ASTM D1586-84 (or 74) [5]), Cone Penetration Tests (CPT) (ASTM D 3441-75T [7]), Marchetti Dilatometer Tests (DMT)[9], and field density tests (ASTM D 1556-8) [2]and ASTM D2922-81 [3]), and also correlated with laboratory compaction tests (ASTM D698-78 [3]).

The CPT tests which were correlated with the Y12 probe were taken with a Begemann friction-sleeve type mechanical cone and those correlated with the ABC probe (footnote 3 in Tables 2 and 3) with an electrical cone which records tip and sleeve resistance simultaneously. Both cones had a 1000 mm^2 cross section area and a 60 degree apex angle at the cone tip. The tests were quasi static using a penetration rate of 20 mm/s.

Standard penetration (SPT) tests were performed with a variety of equipment. Most tests used the rope and cathead method with less than 3 turns of rope around the cathead and donut as well as safety hammers. Some of the tests on Site 1 were performed with free fall drop hammers, but the blow count data indicate that their energy efficiency did not exceed that of the safety hammer tests (no energy measurement equipment was available at the time (1979) these tests were performed). Since the SPT data which were correlated with the probe data were, for the most part, taken prior to the initiation of this project, it could not be ascertained in most cases whether safety or donut hammers were used. It was, therefore, assumed that, on the average, the data represent typical U.S. practice. However, it was established that: (1) no plastic liners were used in the split spoon samplers, and (2) the drillrod length used to take the shallow-depth data which were used for comparison with the HPT was 10 ft (3.05 m).

Funding levels for this project did not permit extensive traditional soil investigations for the sole purpose of obtaining comparative data. Thus, most of the data were obtained by performing helical probe tests alongside ongoing or past exploration projects.

The data were obtained in the Washington, D.C. area and are from two types of surficial geology: the Piedmont and the Atlantic Coastal Plain. The Piedmont is covered by residual soils ranging in particle sizes from silty clays to silty sands. These soils have been formed by the weathering of the underlying bedrock (commonly schist, gneiss or granite). By the Unified Soil Classification System (ASTM D2487-83 [6]), these soils are classified as CL, ML and SM, with the majority of sites falling in the ML range. The Atlantic Coastal Plain Region is mostly covered by sedimentary deposits of clays, silty and clayey sands and sands (CL, CH, ML, MH, SC, SM, SW,and SP).

The greatest problem associated with the interpretation of correlative data from two adjacent soundings is the variation in soil properties. This problem is particularly severe in the residual soils which are not stratified horizontally. The problem is also aggravated when data are confined to shallow depths where soil characteristics are affected by vegetation, frequent changes in moisture content, and cycles of freezing and thawing. Thus, rather than comparing adjacent readings at the same depth, the average values of the HPT torque had to be compared with average values of other in situ measurements for adjacent soundings at any given location, in order to obtain statistically significant correlations. However, in some instances distinct soil strata could be identified in adjacent soundings. In these instances, the soil strata were matched and separate correlations were obtained for individual strata. Some HPT tests were performed in compacted soils and matched against field density and laboratory compaction tests.

The test data are summarized in Tables 2 through 5. Table 2 is for the Piedmont Region and contains tests 1 to 31. Table 3 is for the Atlantic Coastal Plain Region and contains tests 32 to 57. Since most of the conventional exploration data with which the HPT readings are correlated are proprietary, only the general location of the exploration data is identified in Tables 2 and 3.

Tests 47 to 55 were taken with the ABC probe before the Y12 probe was developed. Similarly, data reported in tests 20 to 28 were obtained from Reference [14] and were taken with the ABC probe. For these data, ABC readings were converted to Y12 readings in accordance with footnote 2 in Tables 2 and 3, which is based on the data in Table 4.

For the t_{12}, N, and q_c readings the number of independent data points in each test,n, is identified in the adjacent column. For the D_f, E_D, RC and γ_d data the number of independent data points is identified in parentheses after the value. Readings for q_c are given in kPa x 10^{-2} in order to preserve the convention of reporting these values in bars. All values given are the mean values of "n" data points.

Table 4 gives correlations between the torques of different probe types. Ratios of the average value of the probe torques to the average t_{12} torques are identified by the letter R and given in parentheses. Average ratios for all the data are given at the bottom of Table 4. Note that only few data points are available for t_8, t_{16} and t_{24} correlations. The reason for the small data sample is that the final models for these prototype probes were only developed toward the end of the project. Earlier models had to be modified to improve penetration characteristics.

Table 5 summarizes available data on reverse torque ratios (TR). In this instance the soil properties are not a major variable,

since the reverse torque is taken in the same location as the downward torque by turning the probe 180 degrees counter-clockwise. Averages and standard deviations of TR are given in the Table for the Y12 and ABC probes.

TABLE 2. HPT TEST DATA, PIEDMONT REGION

Test No.	Location	Soil Type	t_{12}, in-lb	n	SPT N blows/ft	n	CPT q_c kPax10^{-2}	n	D_f, kN (n)	E_d, MPa (n)	RC, %	γ_d, Mg/m^3 (n)	Notes
1	McLean, VA	ML	43	62	8.97	51	15.0	40				1.19	
2	Tysons Corner, VA	ML	89	8						23.6 (6)		1.87 (5)	
3	Falls Church, VA	CL/ML	84.6	20	14.7	3			10.7 (5)	13.9 (5)			
4	Falls Church, VA	CL/ML	84.3	14			44.84	3					
5 1/	Falls Church, VA	CL/ML	79.93	18			32.33	6					
6 1/	Falls Church, VA	ML	152.4	3			49.67	3					
7	Falls Church, VA	ML	55	6	11.5	2							
8	Reston, VA	ML	122	6	20	1			7.6 (4)	22.2 (4)			
9	Reston, VA	ML	53	6	14	1							
10	Falls Church, VA	ML/SM	75.6	4							98.7	1.69	Fill
11	Falls Church, VA	ML/SM	68	6							96.7	1.66	Fill
12	Falls Church, VA	ML/SM	45	5							89	1.53	Fill
13	Columbia, MD	ML/SM	45	10	10	2			8.75 (6)	12.8 (6)			
14	Columbia, MD	ML/SM	67	10	10.3	3							
15	Columbia, MD	ML/SM	97	10	15.7	3			13.81(6)	24.4 (6)			
16	Springfield, VA	SM	136.3	6							97.5(8)	1.87 (8)	Fill
17	Springfield, VA	SM	136.3	6							100.2(1)	1.92 (1)	Fill
18	McLean, VA	CL	106	12							97.3	1.98	Fill
19	McLean, VA	CL	110.3	6							97.3	1.98	Fill
20	NBS	ML	37.59 2/	4	9	1							
21	NBS	ML	32.89 2/	4	9	1							
22	NBS	ML	50.75 2/	4	12	1							
23	NBS	ML	56.39 2/	6	11	2							
24	NBS	ML	41.35 2/	4	7	1							
25	NBS	ML	48.87 2/	4	7	1							
26	NBS	ML	42.29 2/	4	14	1							
27	NBS	ML	56.39 2/	4	11	1							
28	NBS	ML	42.60 2/	16			16.57 3/	24	5.01 (5)	5.38 (5)			
29	NBS	ML	61.33 2/	7			35.74 3/	21					
30	NBS	ML	55.76 2/	18			26.56 3/	18					
31	NBS	ML	62.16 2/	10			22.38 3/	9					

1/ Different strata within test boring were matched separately.

2/ Torque t_{12} was calculated from ABC results using: $t_{ABC} = 5.32\ t_{12}$ for sands and silts and $t_{ABC} = 4.27\ t_{12}$ for clays.

3/ Data taken with electric cone. All other data taken with mechanical cone.

TABLE 3. HPT TEST DATA, ATLANTIC COASTAL PLAIN

Test No.	Location	Soil Type	t_{12}, in-lb	n	SPT N, blows/ft	n	CPT q_c, kPax10^{-2}	n	D_f, kN (n)	E_d, MPa (n)	RC, %	γ_d, Mg/m^3 (n)	Notes
32	Chesapeak, MD	SM	38	22	9.3	3						190 m/s<$v_s \leq$220 m/s	
33	Chesapeak, MD	SM	58.9	22	11.7	3							
34	Annapolis, MD	SM	58.5	10	9.5	2							
35	Annapolis, MD 1/	SM	36	7			25	4					
36	Annapolis, MD 1/	SM	92	3			83	5					
37	Annapolis, MD 1/	SM	55	5			46	5					
38	Annapolis, MD 1/	SM	140	5			77	5					
39	Lorton, VA	SC	58	10			52.71	7					
40	Arlington, VA	CL	34.8	3	6	1							
41	Arlington, VA	CL	74.6	3	47	1							
42	Arlington, VA	CL	24	1	6	1							
43	National Airport	SC	121	3	16	1							
44	National Airport	CL	120	1	17	1							
45	National Airport	SM/SC	58.22	9			53	8					Fill
46	Lanham, MD	SC/CL	102	4	14.3	3							
47	Laurel, MD	SW/SM	47.56 2/	6			28.9 3/	12					
48	Laurel, MD	SW/SM	57.41 2/	7			39.7 3/	14					
49	Crofton, MD 1/	SC	45.49 2/	4			36.18 3/	4					
50	Crofton, MD 1/	SC	18.98 2/	2			17.9 3/	2					
51	Crofton, MD	SC	30.03 2/	8			21.29 3/	27					
52	Crofton, MD	CL	31.12 2/	8			19.53 3/	19					
53	Odenton, MD	SP	65.79 2/	8	18	1						D_{50} =	0.7mm
54	Upper Marlboro, MD	CL	17.56 2/	3	6	1							
55	Upper Marlboro, MD	CL	23.42 2/	3	4	1						D_{50} =	0.03mm
56	Crofton, MD	CL	18.91 2/	2			11.8 3/	6					
57	National Airport	SM/SC	54	10			52	7					

1/ Different strata within test boring were matched separately.

2/ Torque t_{12} was calculated from ABC results using t_{ABC} = 5.32 t_{12} for silts and sands and t_{ABC} = 4.27 t_{12} for clays.

3/ Data taken with electric cone. All other data taken with mechanical cone.

TABLE 4. CORRELATION BETWEEN HPT PROBE TORQUES

Test No.	Location	Soil Type	t_{12} (R_{12})	n	t_{ABC} (R_{ABC})	n	t_8 (R_8)	n	t_{16} (R_{16})	n	t_{24} (R_{24})	n
1	McLean, VA	ML	(1)	52	(5.35)	52						
6a 1/	Falls Church, VA	ML	60.6 (1)	8	308.28 (5.09)	8						
34a	Annapolis, MD	SM	63 (1)	14 2/			38.43 (0.61)	7	80.71 (1.28)	7	206.71 (3.28)	7
40a	Arligton, VA	CL	63.48 (1)	7	217.32 (3.42)	7						
44a	National Airport	CL	62 (1)	14	262.14 (4.23)	14						
46a	Lanham, MD	SM	90 (1)	2			45 (0.5)	2	170 (1.98)	2		
13,14a	Columbia, MD	ML/SM	79 (1)	2							240 (3.04)	2
	Summaries		(1) (1)	60 21	(5.32) ML (4.27) CL	60 21	(0.59)	9	(1.44)	9	(3.22)	9

For Y8, Y12, Y16, and Y24 : $t_i/t_{12} \simeq 0.4 + 0.7(d/d_{12})^2$ where d = OD of probe

1/ The "a" after the test number indicates that the data sample used in this table is not the same used in Tables 2 and 3.

2/ Two different Y12 probes were used in adjacent soundings and their readings averaged.

TABLE 5. REVERSE TORQUE RATIO

Test No.	Location	Soil Type	TR_{12}	sTR_{12}	n	TR_{ABC}	sTR_{ABC}	n
39	Lorton, VA	SC	30	11	10	44	11	10
43	National Airport	SC	31	8	10	34	5	8
13	Columbia, MD	SM	29	9	10			
13	"	SM	27	5	10			
13	"	CL	42	14	10			

4. ANALYSIS OF RESULTS

4.1 Correlation between SPT and HPT

Figure 7 shows a plot of the Y12 torque against the SPT blowcount "N". The data can be identified in Tables 2 and 3 by the test number next to each plotted point. The number in parentheses next to the test number is the number of independent data points in the test. The plotted test points are taken from Tables 2 and 3 and represent the average values calculated from independent data points. Silty (residual) soils are shown by triangles, clayey soils by circles and sandy soils by squares.

The weighted average for all the data points, obtained by a linear regression analysis through the origin is represented by the line:

$$N = 0.2t_{12} \qquad \text{... (Eq. 1)}$$

Note that the scatter of the data is at least in part attributable to the difference in soil properties between adjacent borings. For the data shown in Figure 7, approximately two-thirds of the data points would fall between the lines:

$$N = 0.17\ t_{12} \text{ and } N = 0.23\ t_{12}$$

and 90 percent would fall between the lines:

$$N = 0.15\ t_{12} \text{ and } N = 0.25\ t_{12}.$$

The correlation between t_{12} and N does not appear to be sensitive to the particle size characteristics of the soils (sandy, silty or clayey). Lines B and B' and A and A' in Figure 8 represent the boundaries between which 2/3 of all the data points and 90 percent of the data points, respectively, are estimated to fall if the assumption is made that the variance of the blowcount N (s^2) corresponding to a given torque is proportional to the magnitude of the torque.

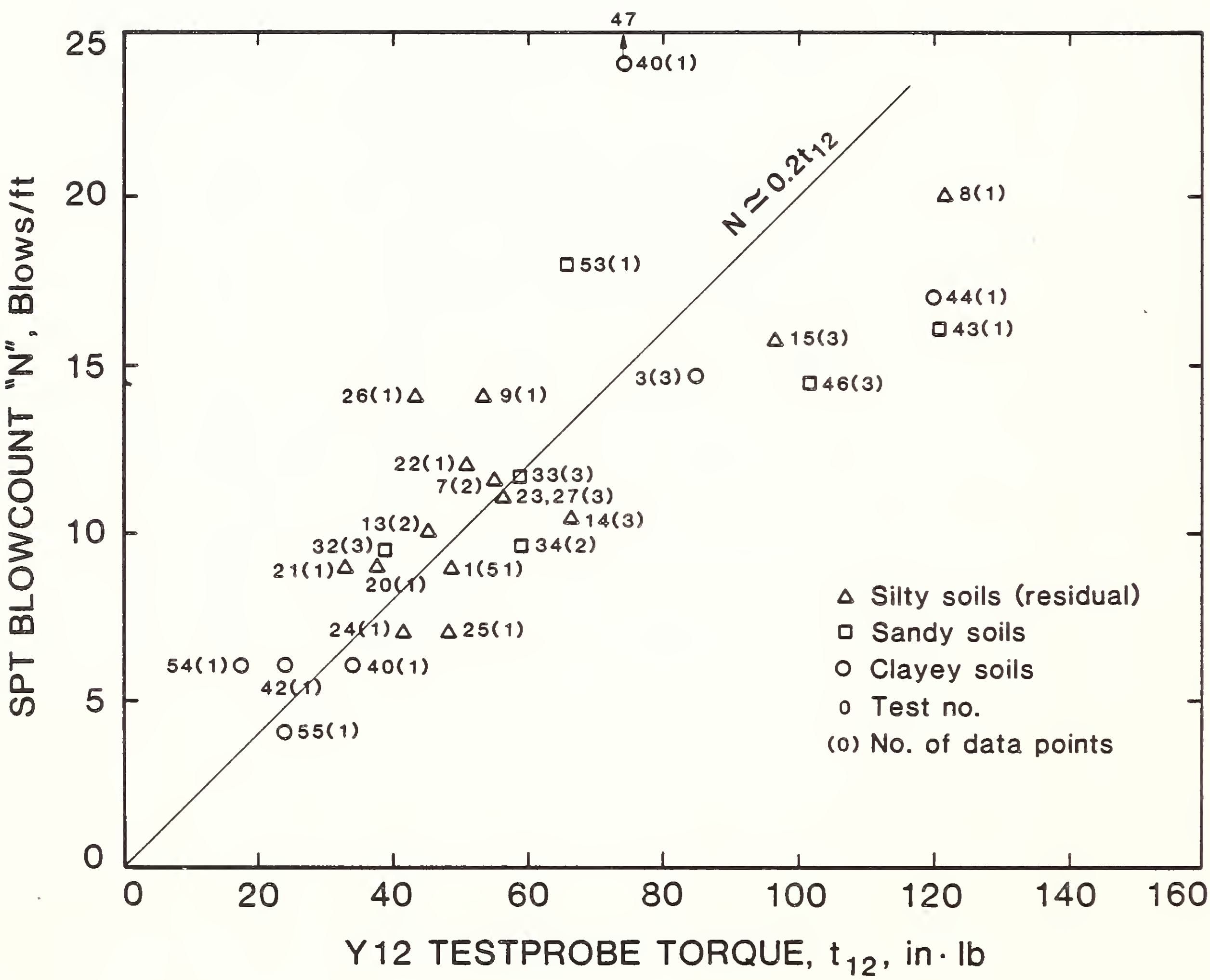

Figure 7 Correlation Between SPT and HPT Tests

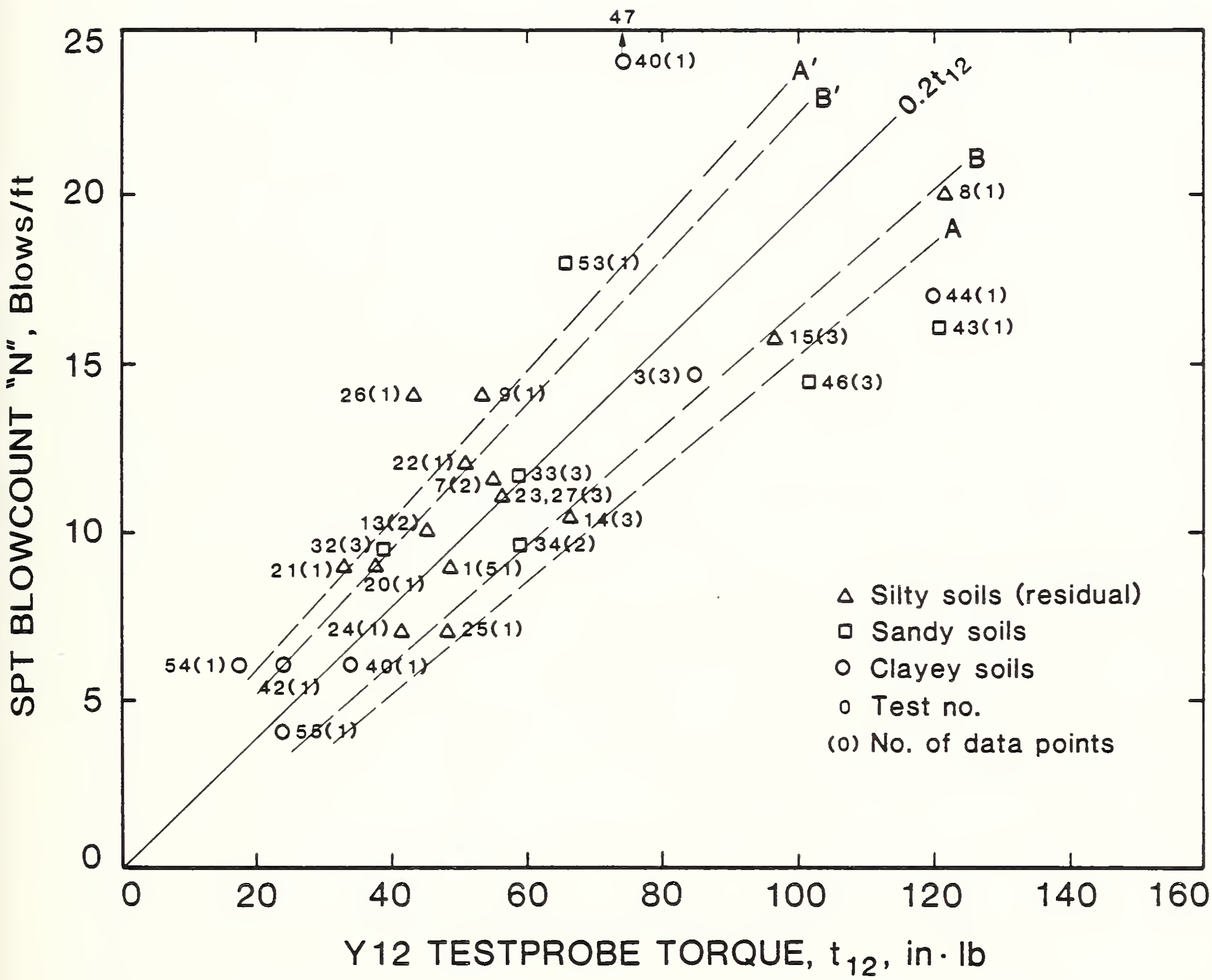

Figure 8 Confidence Bands for the SPT-HPT Correlation Assuming that the Variance of N is Proportional to the Corresponding t_{12}

As previously noted, the SPT data were taken with a 10 ft (3.035 m) drillstem length. Since for shallow depths the energy loss associated with the short drillstems used makes the blowcount obtained in an SPT test sensitive to the depth at which the test is taken, while the HPT or CPT data are not similarly affected by depth, a comparison between SPT and HPT tests should also be made for results that would be obtained at a depth where the SPT is no longer affected by drillstem length. The energy loss associated with short drillstems is affected by the drillrod mass which is the product of the mass density of steel and the drillrod volume. The drillrod volume, in turn, depends on the rod type used. Drillrod sizes used could not be ascertained for all the test data, but it was determined that A rods were used in tests 20 to 27 which account for 9 data points and N rods were used in Test 1 which accounts for 51 data points.

The short drillstem effect can be calculated in accordance with Reference [13], as: $E_r = 1 - \exp(-4M_r/M_h)$ ... (Eq.2)

where: E_r = the ratio of the energy transmitted by the short rod to the total energy transmitted through the rod

M_r = the mass of the short drillrod

M_h = the mass of the SPT hammer = 63.5 kg.

"A" rods have a mass of 5.9 kg per meter length and N rods 7.04 kg per meter. Accordingly, a 10 ft (3.05 m) long A rod will transmit 68 percent of the energy transmitted by a long rod and a 10 ft long N rod 74 percent. Thus, a reasonable correction for the average rod length effect on the data in Figure 4 can be made by multiplying the N values by 0.7. Therefore, if a long drillrod were used the average correlation between t_{12} and N could be reasonably approximated by the expression:

$$N = 0.14\ t_{12} \qquad \text{... (Eq. 3)}$$

4.2 Correlation between CPT and HPT

Figure 9 shows a plot of the Y12 torque versus the CPT tip

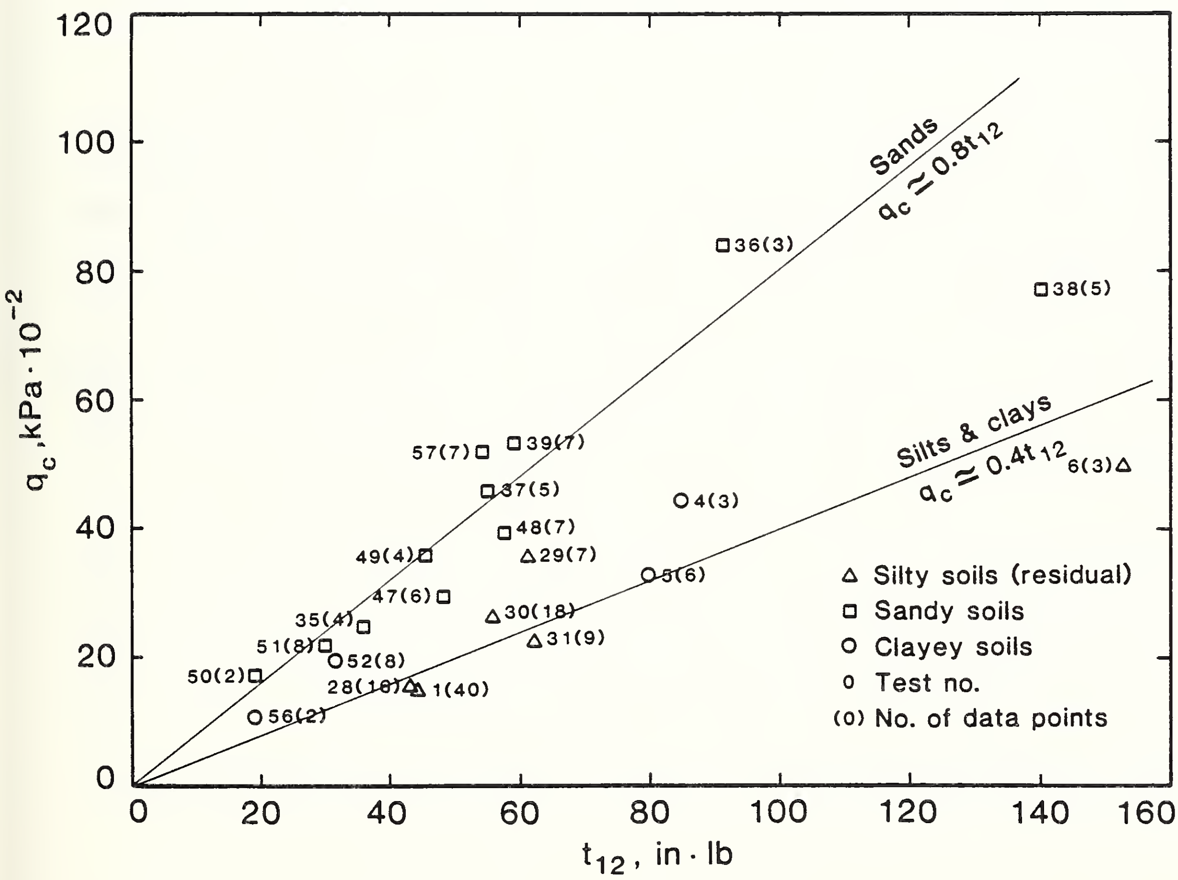

Figure 9 Correlation Between CPT and HPT Tests

resistance, q_c. Figure 9 contains data taken with a mechanical cone, as well as several data points taken with an electrical cone. (It is realized that the cone type used has some effect on penetration resistance (for instance Reference [12] Figure 1.7). No correction was attempted to account for this effect).

It is apparent from an examination of Figure 9 and from an analysis of the data that the correlation is sensitive to the soil type. For the sandy soils, the weighted average for all the data points, obtained by a linear regression analysis through the origin is represented by the line: $q_c = 0.8\ t_{12}$ ...(Eq. 4)
Approximately 2/3 of the data fall between $q_c = 0.67\ t_{12}$ and $q_c = 0.93\ t_{12}$, and 90 percent of the data between $q_c = 0.58\ t_{12}$ and $q_c = 1.02\ t_{12}$.

Lumping all the silty and clayey soils together (the Piedmont soils and clayey soils from the Atlantic Coastal Plain) the weighted average for all the data points is represented by the line: $q_c = 0.4\ t_{12}$ ...(Eq. 5)
Approximately 2/3 of the data points fall between $q_c = 0.32\ t_{12}$ and $q_c = 0.48\ t_{12}$ and 90 percent of the data between $q_c = 0.27\ t_{12}$ and $q_c = 0.53\ t_{12}$.

Lines B and B' and A and A' in Figures 10 and 11 represent the boundaries between which 2/3 of the data points and 90 percent of the data points for the sands and silts, respectively, are estimated to fall if the assumption is made that the variance of the q_c values corresponding to a given torque is proportional to the magnitude of the torque.

4.3 Consistency between the SPT/HPT and CPT/HPT Correlations

It has been previously concluded by the analysis of separate samples of test data that the correlation between t_{12} and N is not sensitive to the soil type and that the average value of that

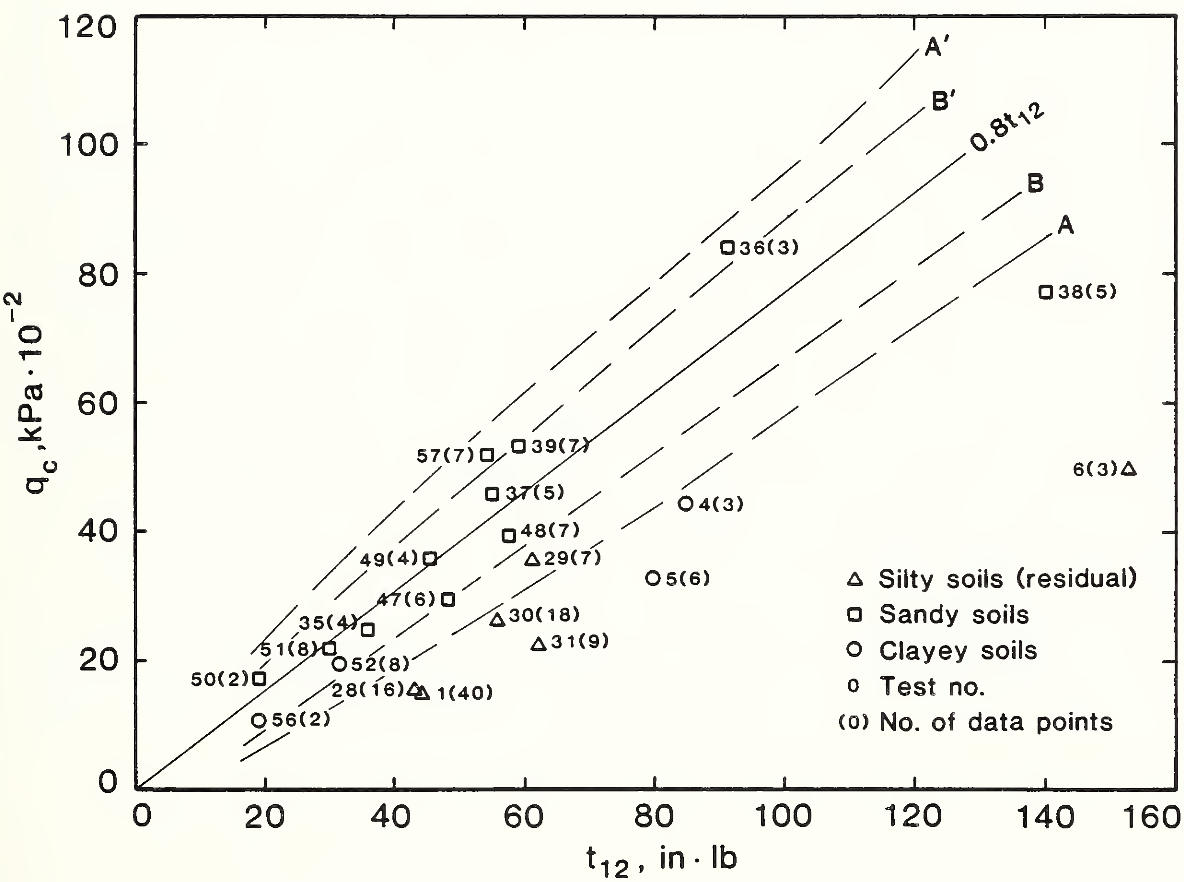

Figure 10 Confidence Bands for the CPT-HPT Correlation for the Sandy Soils Assuming that the Variance of q_c is proportional to t_{12}

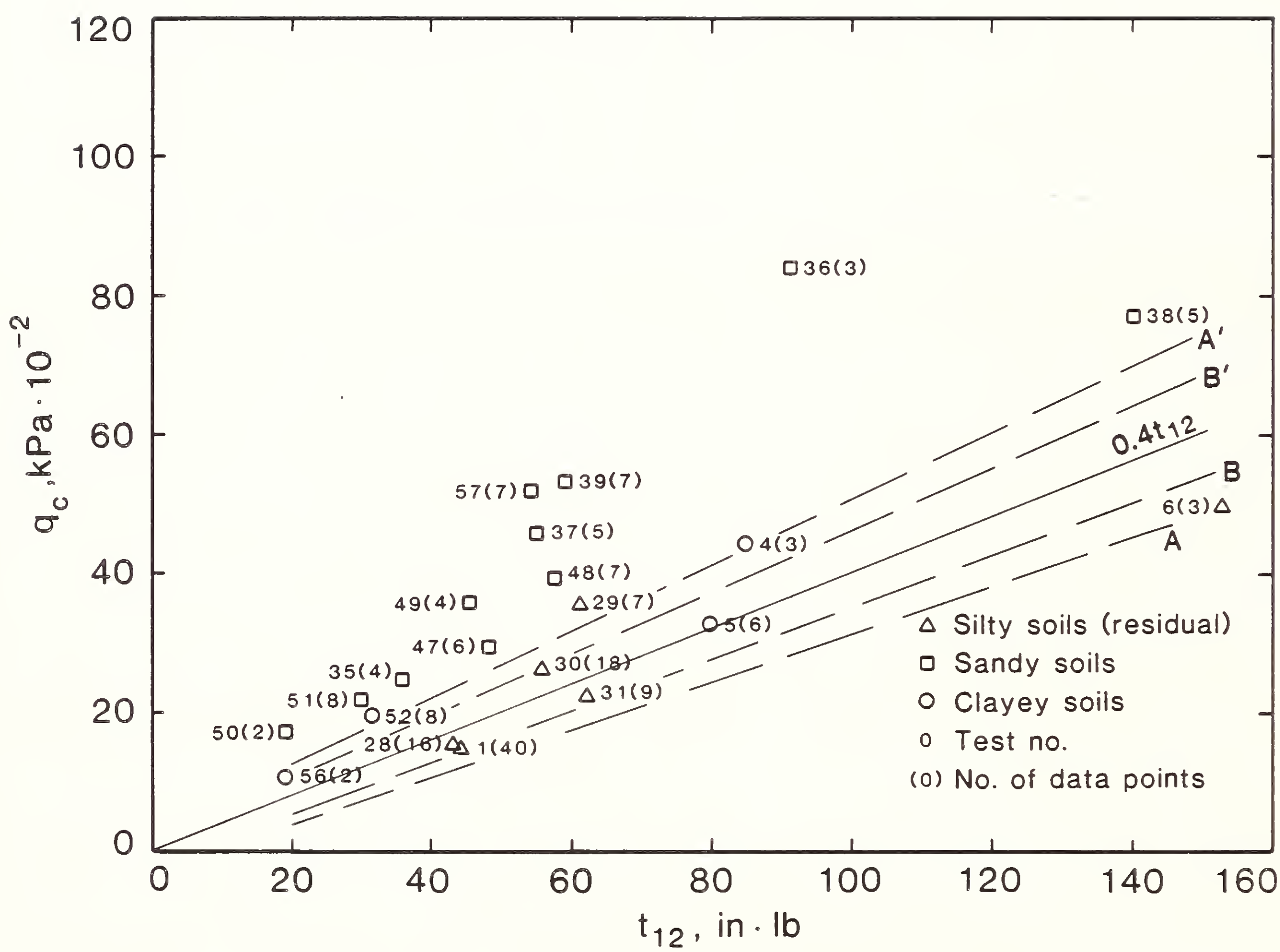

Figure 11 Confidence Bands for the CPT-HPT Correlation for the Silty and Clayey Soils assuming that the Variance of q_c is proportional to t_{12}

correlation is approximately $N = 0.2\ t_{12}$ if 10 ft long drill stems are used in the SPT and $N = 0.14\ t_{12}$ if long drill stems are used (an "A" rod would have to be about 6m long, and an "N" rod about 5m long to transmit 90 percent of the energy) and that the correlation between t_{12} and q_c is sensitive to the soil type and averages approximately $q_c = 0.8\ t_{12}$ for the sandy sites, and $q_c = 0.4\ t_{12}$ for the silty and clayey sites. If these conclusions are valid, then the correlation between the Standard Penetration Test and the Cone Penetration Test must also be sensitive to the soil type and must be approximated by the following expressions:

$q_c = 5.7$ N for the sandy sites

$q_c = 2.9$ N for the silty and clayey sites

where q_c is in kPax10^{-2} (bars) and N is in blows per ft. (The long drillstem value of N has been used for the comparison, since most published data are based on SPT data for reasonably long drillstems).

Since a considerable body of data on SPT-CPT correlation has been published in the literature, the validity of the conclusions in sections 4.1 and 4.2 can, therefore, be tested. Figure 12, which is taken from Robertson et al. (1983) [11] summarizes SPT-CPT correlations for available data. According to the authors, the solid line in Figure 12 represents the SPT-CPT correlation for an energy ratio of 55 percent which is a reasonable average for typical U.S. practice, using rope and cathead and donut as well as safety hammers [8] (some experts believe this average to be higher because of recent increases in the use of safety hammers). SPT results from donut hammers should fall somewhat below the line, and those from safety hammers above the line. Soils are characterized by the particle size at which 50 percent of the soil by weight is finer, D_{50}, in mm.

An examination of Figure 12 shows that the q_c/N ratio of 2.9 falls in the particle size range of silty soils (D_{50}= 0.03 mm)

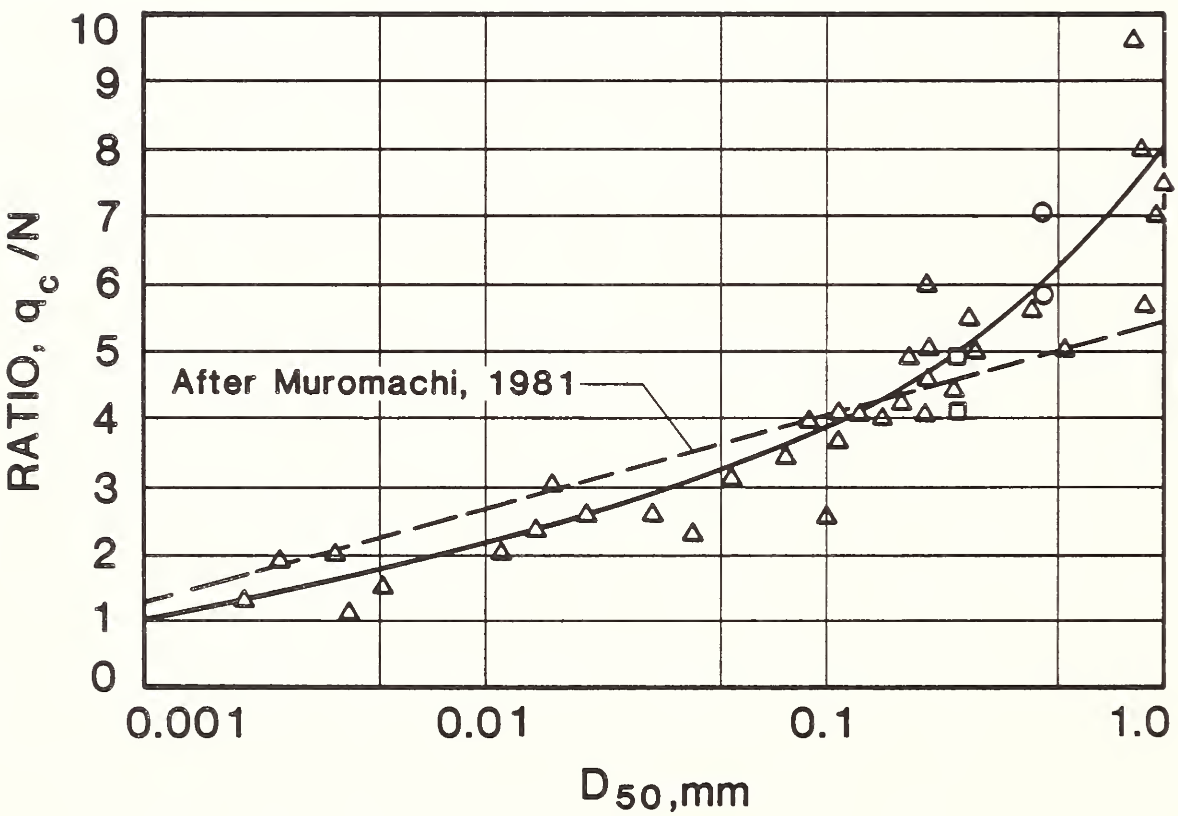

Figure 12 Variation ofthe q_c/N ratio with D_{50} (Taken from Robertson et al.[11])

and the q_c/N ratio of 5.7 falls in the range of sandy soils (D_{50} = 0.3 mm). Thus, the ratio between the average N/t_{12} and q_c/t_{12} values for silty and sandy soils are reasonably consistent with the data presented in Figure 12.

A large concentration of CPT data points is provided by Tests 1 and 28. Test 1 is from McLean, VA and has 40 data points. Test 28 is from the NBS campus and has 16 data points. Both tests are in residual silts of similar characteristics, and their average CPT and HPT values are almost identical. The combined average q_c/t_{12} ratio for these two tests is 0.36. At the McLean site, particle size analyses were performed for a depth profile from 10 to 60 ft (3 to 20 m). D_{50} for the most shallow sample at 10.5 ft depth was 0.018 mm. For the deeper samples D_{50} tended to fall between 0.02 to 0.03 mm, with two exceptions where it was 0.1 mm. If it is assumed that the 0.018 mm D_{50} size of the 10 ft deep sample is typical for the shallow depth, the corresponding q_c/N value from Figure 12 would be about 2.46. If it is assumed that t_{12} = 0.14N, the corresponding q_c/t_{12} value would be 2.46 x 0.14 = 0.35, which is very close to the measured value of 0.36. Unfortunately, D_{50} data are not available for the other fine grained soils in the data sample. However, the average q_c/N value of 2.9 seems reasonable and consistent with the data in Reference [11].

The average q_c/N value for the sandy test sites falls within the range of sands in Figure 12. Unfortunately, data on the D_{50} sizes are not available for the sandy sites. The sands in tests 47 and 48 were characterized in the field as brown, fine to medium sand. The average q_c/N value for this site is 4.35 if N is assumed to be 0.14 t_{12}. If it is assumed that D_{50} for this sand falls between 0.1 mm and 0.3 mm which is a reasonable estimate for the field classification of "fine to medium", the value of q_c/N in accordance with Figure 12 should fall between 4 and 5.5 which is the case in this instance.

There are no other data from which D_{50} values for the sandy sites could be derived, but there is another source of information, the percent of fines (percent by weight of particles passing #200 sieve). Muromachi (1981) [10] developed a correlation between the q_c/N ratio and the percent of fines, based on available data in Japan. He suggested the equation:

$$q_c/N = 4.76 - 0.02 \text{ F.C.} \qquad \text{...(Eq. 6)}$$

where F.C. = percent of fines by weight. Muromachi's data generally yield larger values for q_c/N ratios for fine grained soils, and smaller values for sands than those derived by Robertson et al. This can be seen by the broken line in Figure 12, which is a curve which Muromachi developed for the D_{50} value from the same data base that was the basis for equation 6. The reason for the discrepancy between Muromachi's and Robertson's curves is probably a narrower range of particle sizes in the Japanese data base.

In the Piedmont soils, the percent of fines generally ranges from 65 to 85 percent. By Muromachi's equation this would yield a range of q_c/N ratios from 3 to 4, which is somewhat higher than the 2.9 average ratio obtained from the HPT data. For sandy sites, data on the percentage of fines are available for tests 34 to 38, where the range is 25 to 36 percent. Using equation 6, this would result in a q_c/N ratio between 4.05 and 4.25. The actual average calculated q_c/N ratio for these tests is 4.77. Thus, as in the case of the comparison between Muromachi's and Robertson's curves, the q_c/N value from Muromachi's equation (Eq. 6) is higher for the fine grained soils and lower for the sands than the values derived from this test program.

Figure 13 shows a plot of the data points on a diagram for q_c/t_{12} correlations derived from equation 3 and the solid curve in Figure 12. It may be noted that some of the tests classified as "clays" (CL) have high q_c/N ratios (tests 52 and 56). These

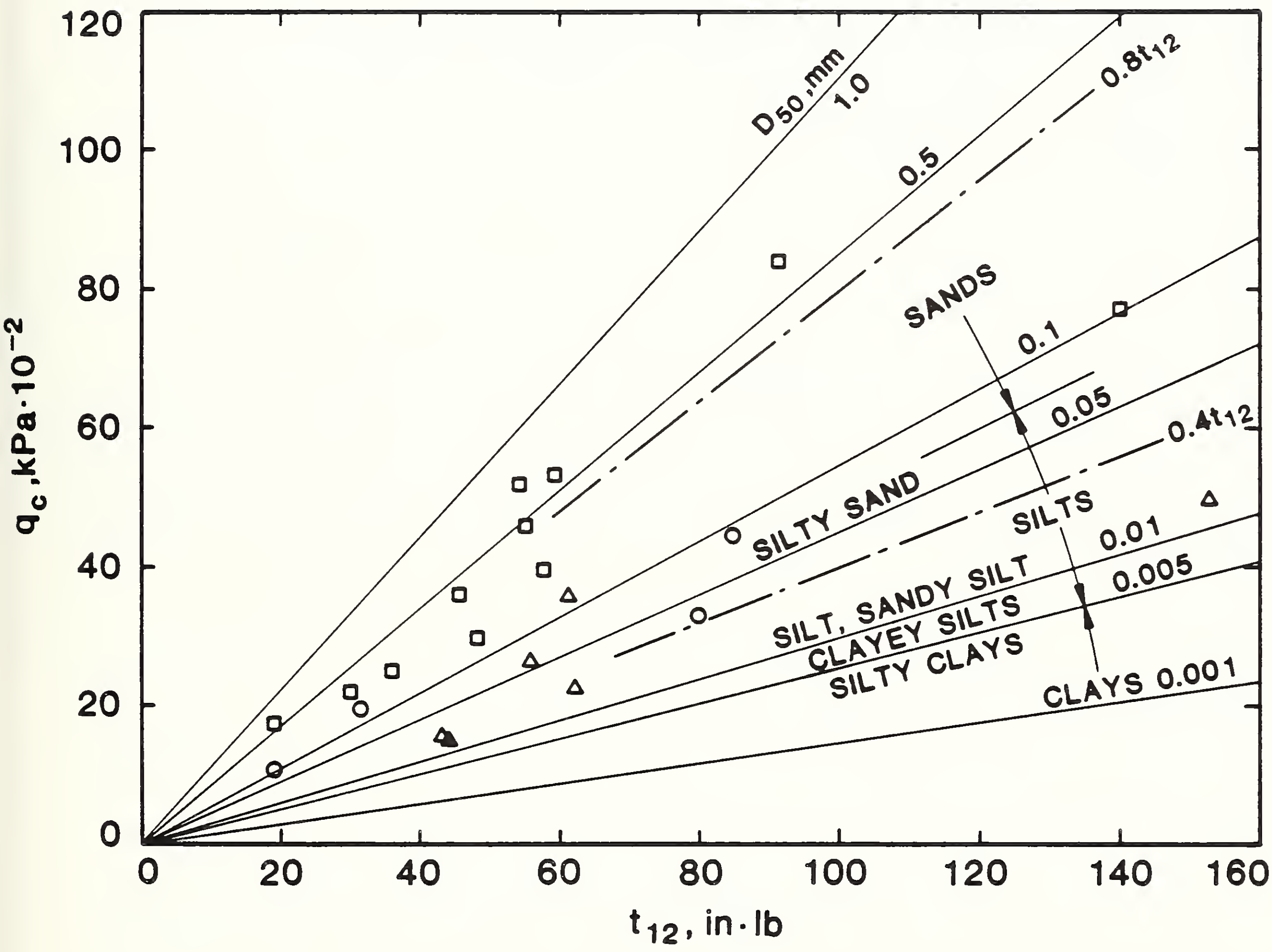

Figure 13 Comparison of Test Data with the Correlation Between q_c and t_{12} as a Function of D_{50}

soundings were taken in the Atlantic Coastal Plain alongside other tests (49 to 51) which were classified as "sandy soils". It is possible that these soundings were actually in sandy soils (the HPT test does not include retrieval of soil samples).

In general, it can be concluded that for the silty and sandy soils the correlation between the SPT/HPT and CPT/HPT data are consistent with the trend of CPT/SPT correlations observed by Robertson et al. (Figure 12). The data for clayey soils are inconclusive. Using equation 3 and the solid curve in figure 12, the following equation for the HPT/CPT correlation as a function of the particle size characteristics of the soil was derived:

$$q_c/t_{12} = 1.09(D_{50})^{0.29} \qquad \text{... (Eq. 7)}$$

Equation 7 is plotted in Figure 14.

4.4 HPT Tests in Compacted Soils

Figure 15 is a plot of t_{12} against the in-place dry density $_d$, and relative compaction as determined by ASTM tests D1556 or D2922 and D698 [2,3,4]. The tests involve silty, clayey and sandy sites. Points 10, 11, and 12 are from the same site, taken at different locations.

The correlation between dry density and t_{12} for the silt and clay sites seems to fall into a pattern (tests 12, 11, 10, 2, 18 and 19) and could be approximated, within the range of the densities measured, by the equation: $1.2+0.0063\ t_{12} < \gamma_d \leq 1.2+0.0075\ t_{12}$ (Eq. 8) where: γ_d is in tons per m^3 (Mg/m^3) and t_{12} is in in-lb.Since the range of the densities in Figure 15 is approximately the range of densities that could be expected for compacted soils in the Piedmont region, it may be possible to establish a correlation which could be used for the whole region. Note that the sandy site does not fall within this pattern.

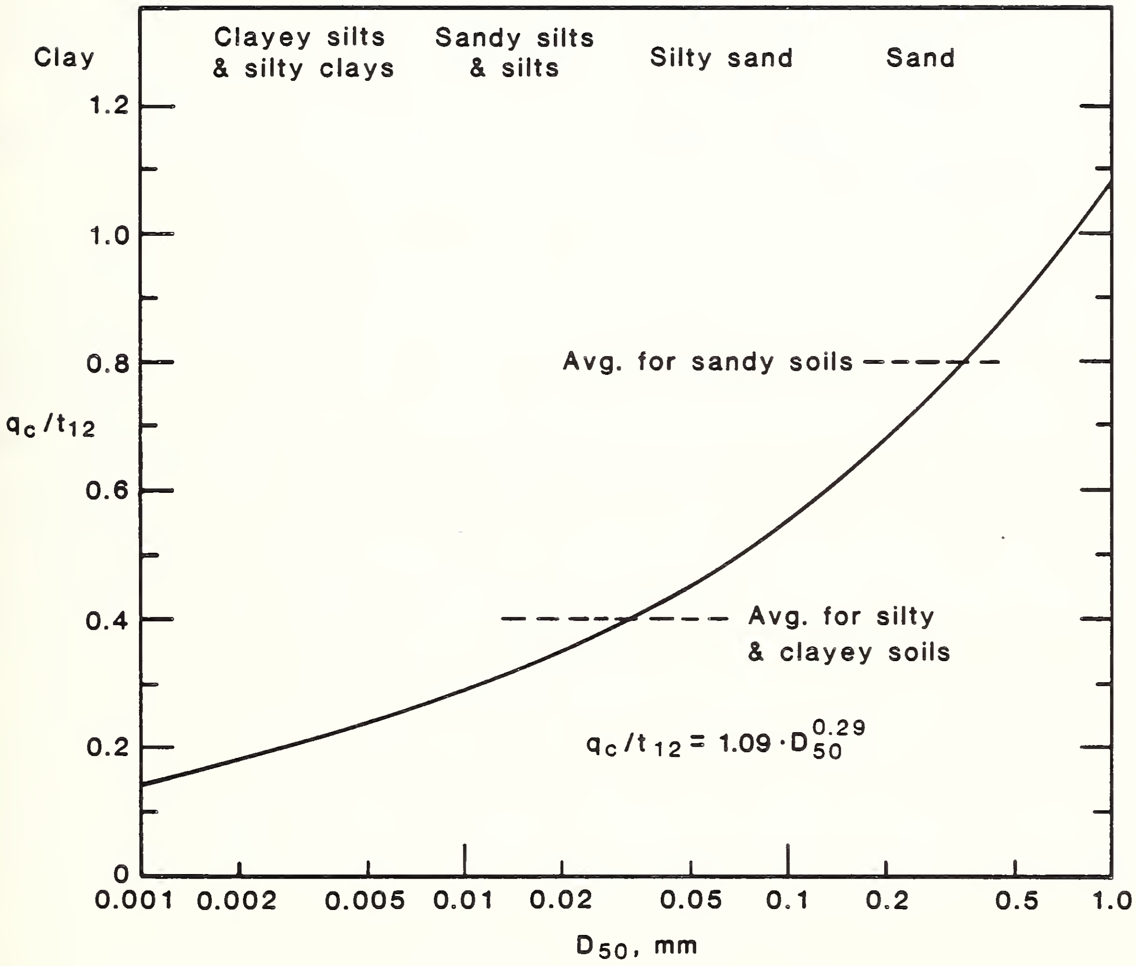

Figure 14 Correlation Between q_c/t_{12} and D_{50}

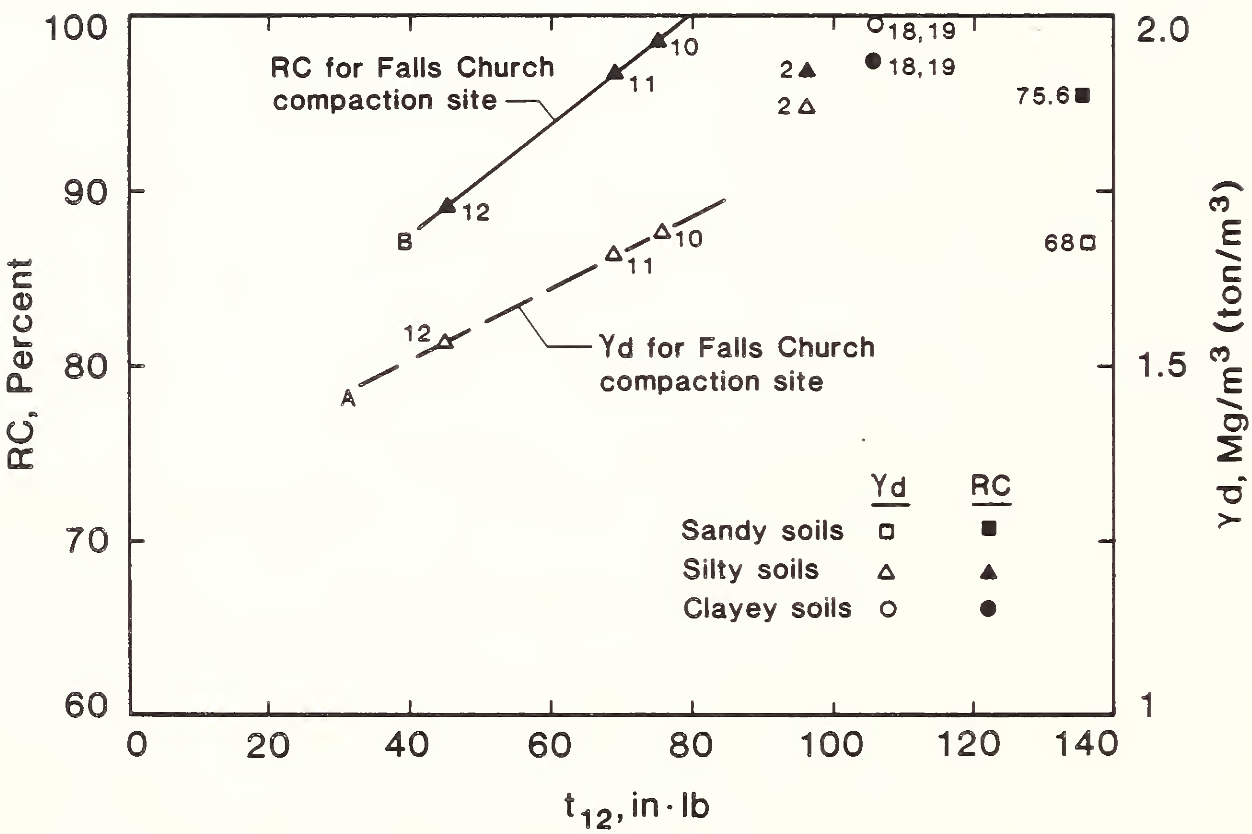

Figure 15 Correlation Between t_{12}, γ_d, and Relative Compaction for Compacted Soils

Even more promising is the plot for a single site in Falls Church, VA, tests 10, 11, and 12. It appears that, once such a correlation is established for a site by calibration against in place density tests, the relative compaction could be determined by HPT tests with a great degree of accuracy. For instance, for the Falls Church site, the percent of compaction can be determined by the equation: $RC = 75 + 0.32\ t_{12}$ ... (Eq. 9)
where: RC = relative compaction in percent.
The correlation is shown by line B connecting the shaded points 10, 11, and 12. Similarly, the density can be accurately predicted by line A connecting the unshaded points 10, 11, and 12. Equation 9 shows that t_{12} is very sensitive to relative compaction, with each 3 in-lb of torque representing 1 percent of RC.

Thus available data indicate, that the HPT test is an effective tool for predicting the degree of compaction of silty soils, and probably would also work well in clayey and sandy soils, provided there are no obstructions to penetration. It would be superior to present methodology for two reasons:

1. The test is much more convenient and economical than the sand cone test and can be carried to a 1.8 m depth, providing a depth profile of field densities.
2. The test does not require follow-up laboratory work thus eliminating time delays. This would enable engineers and contractors to monitor the construction work while it is in progress, eliminating the need for costly remedial measures after the earth-moving work is completed.

Since density tests, particularly the sand cone test, are taken at or near the surface, while the HPT test penetrates to a depth, it is important to determine how deep below the surface the tip of the helix must penetrate to produce a valid measurement.Table 6 shows the record of Test #11, which was in compacted residual silts.

Table 6. Record of HPT Test

Depth of Tip, ft	t_{12}, in-lb
0.5	48
1.0	66
1.5	68
2.0	62
2.5	71
3.0	68
3.5	72
4.0	50
4.5	26
5.0	38

In this case, the soil was compacted to a depth of 3 1/2 to 4 ft. However, the first reading, with the tip of the Helix at 6 inch depth and the top of the helix near the surface, was low, even though the soil at the surface was probably compacted. The 1 ft deep reading appears to be consistent with the deeper readings. The plot of other HPT tests in compacted soil is shown in Figure 16. Again, it is evident that the 0.5 ft reading is low, and even the 1ft reading appears somewhat on the low side. A similar phenomenon can be observed in other penetration tests, for instance the CPT. The lower resistance at a shallow depth is attributable to the low confining pressure and also to the failure mechanism associated with the displacement of soil at the tip of the penetration device and the expansion of a cavity in the soil. Another factor contributing to the lower resistance at the shallow depth is the fact that it is difficult to hold the shaft of the HPT in a stable position until some penetration is achieved.

On the basis of the data available to date, it is recommended to use HPT readings at 1 ft (0.3 m), and preferably at 1.5 ft or deeper to determine compaction. Of course it may also be possible to adapt the Y8 probe for shallow-depth measurements, or to calibrate the 6 inch deep readings of the Y12 probe against in-place density.

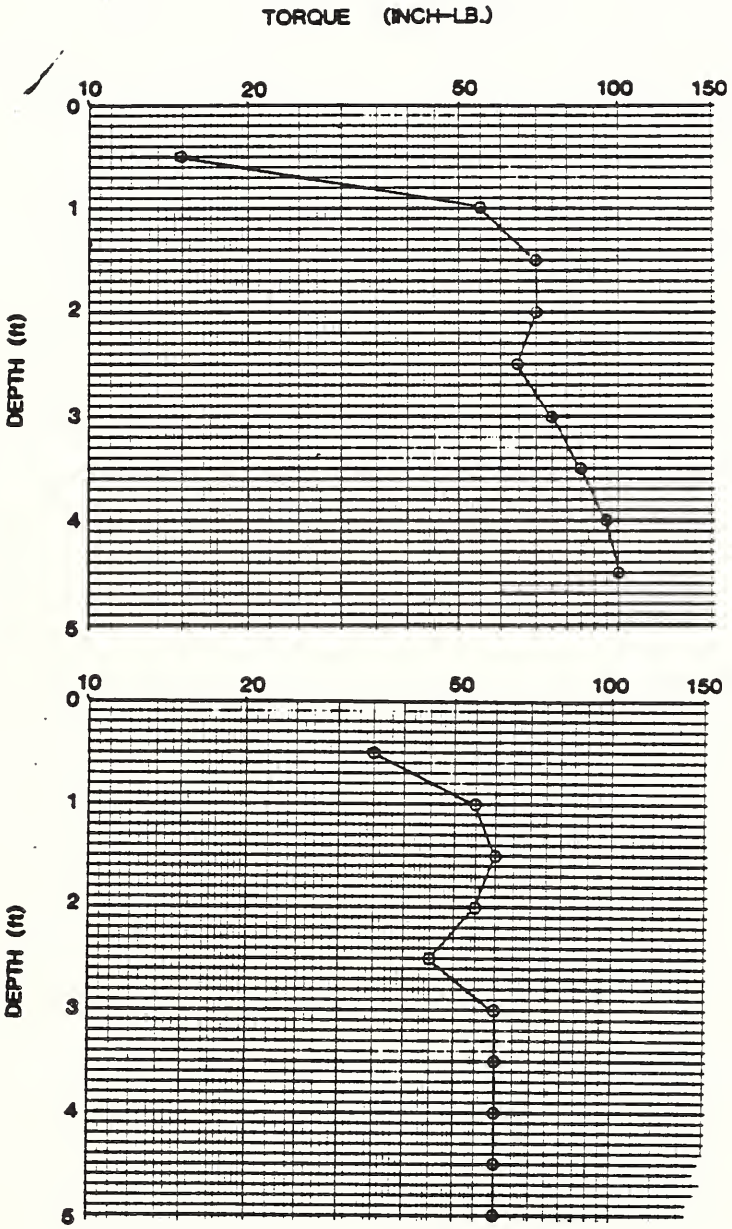

Figure 16 Example of HPT Tests in Compacted Soils

4.5 Correlations between DMT and HPT

In Figure 17, t_{12} is plotted against E_D, the dilatometer modulus, and D_f, the force required to advance the dilatometer. These two dilatometer measurements are quasi independent. E_D, which has been defined by Marchetti (1980) [9] as: $E_D = E/1-\nu^2$ ...(Eq. 9) where E = Young's modulus and ν = Poisson's ratio, and is calculated from the pressures exerted against an expanding membrane, is a measure of soil stiffness. D_f, on the other hand, is a measure of soil resistance to penetration, which is related to soil strength. In reality, these two independent measurements are often related.

There are not many data points in Figure 17, however, it appears from the trend of the data points that t_{12} correlates with both, E_D and D_f. Approximate tentative correlations are:

$$E_D = 0.21\ t_{12} \qquad \text{... (Eq. 10)}$$

where E_D = dilatometer modulus in MPa, and

$$D_f \quad 0.14\ t_{12} \qquad \text{... (Eq. 11)}$$

where D_f = force required to advance the dilatometer, in kN. For the data plotted, the particle size characteristics did not appear to have a significant effect on the E_D/t_{12} and D_f/t_{12} ratios.

4.6 Reverse Torque Ratio (TR)

Reverse torque ratios are given in Table 5. In this instance, the spatial variability of soil properties does not affect the data, since the reverse torque is taken at the same location as the downward torque, by making a 180 degree counter-clockwise turn. In the silty and clayey sands, the average reverse torque ratio for the Y12 probe was 29 percent. The test results were quite consistent for different depths at the same borings and for different borings with similar soil characteristics, with the

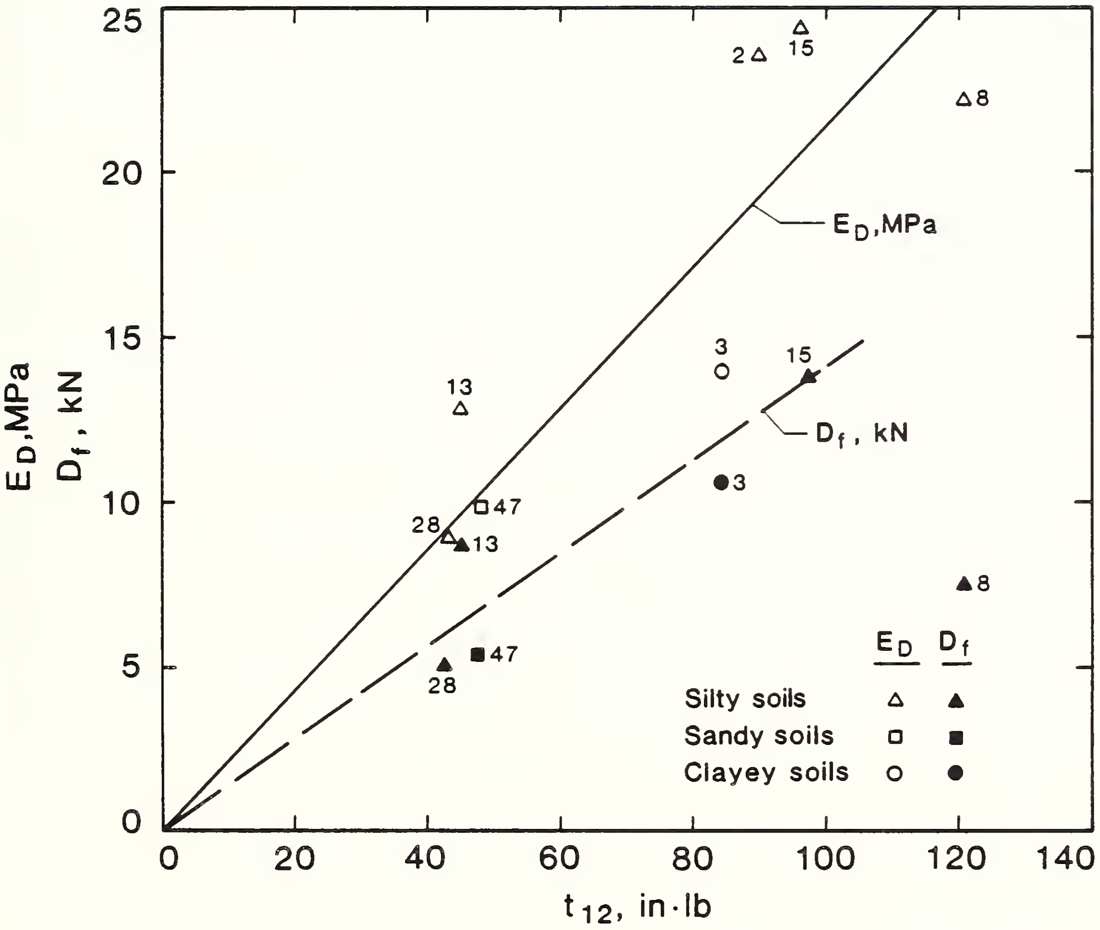

Figure 17 Correlations Between t_{12} and Dilatometer Measurements

clayey sands developing somewhat larger reverse torque ratios than the silty sands. Reverse torque ratios for the ABC probe tended to be larger, and the results less consistent than those from the Y12 probe.

For clays there are data from a single sounding, where TR_{12} was 42 percent, significantly higher than for the sands.

The data sample is too small to draw conclusions, but it is hoped that the sensitivity of the reverse torque ratio to the soil type will be sufficient to provide information on the grain size characteristics of the soil. Such information would be helpful, since present HPT procedures do not include extraction of soil samples.

Another interesting observation is that the reverse torque ratio in the HPT is much higher than the friction ratio (ratio of side friction to tip resistance) in the CPT. This difference may be in part responsible for the difference in the sensitivity of these two tests to the grain size characteristics of the soil.

It can be concluded from the data presented in Table 5 that the torque required to penetrate the soil and expand the cavity within which the helix slides downwards was approximately 70 percent of the total torque in sands, and 60 percent of the total torque in clays.

4.7 Correlation between t_{12} and in situ shear strength

In this test program, no attempt was made to correlate in situ shear strength with t_{12}. However some available data are reported in this section. Yokel et al. [14] correlated the in situ shear strength of residual silts from the Piedmont region, and sands from the Atlantic Coastal Plain region, as calculated from the pullout strength of shallow soil anchors, with the

average ABC torque over the depth of the anchor. In that instance the question of drained vs. undrained strength did not arise, since the soils were relatively pervious and also were not fully saturated. The result of these data, converted into t_{12} torque, is approximated by the following equation:

$$s_u = 1.5\ t_{12} \qquad \ldots \quad \text{(Eq. 12)}$$

where s_u = in situ shear strength in kPa.

A reasonable lower bound for the in situ shear strength in silty and sandy soils is: $s_u = 1.27\ t_{12}$ ...(Eq. 13).

For the shear strength of clays, the data in Reference 14 are inconclusive. The question also arises whether the drained or undrained strength is pertinent to the cases considered. Adams et al. (1972) [1] presented some data correlating the shear strength of clays, as measured by in situ shear vane tests in the field and unconfined compression tests in the laboratory with the torque of the ABC probe. While their data indicate that, for a given soil, there is a definite correlation between t_{ABC} and the shear strength, the correlation differed for different soils, and no general conclusion can be drawn from the data.

5. CONCLUSIONS

The following conclusions can be drawn from the data presented in this report. It should be realized, that the data base is limited, and that some of the correlations which were developed from the existing data base will have to be modified as new data become available:

(1) The helical probe test (HPT) was found to be a practical and economical method for in situ testing of soils at a shallow depth. It correlated well with traditional in situ testing methods and is also applicable to compaction control.

The probe penetrates well into moist or saturated silts, clays, and sands, but difficulties may arise in desiccated soils, dry sands, and soils containing rock fragments. Penetration is also difficult to achieve in dense sands and hard clays.

(2) The most practical size of the HPT probe for competent soils is the 3/4 inch (19 mm) O.D. helical probe, equipped with a 150 in-lb torque meter. A 1-1/2 in (38 mm) O.D. helical probe may be more practical in very soft (or loose) soils.

(3) The correlation between the SPT and the HPT tests is independent of the grain size characteristics of the soil and can be approximately expressed by the following equations:

$N = 0.2\ t_{12}$ for 10 ft long drillstems

$N = 0.14\ t_{12}$ for long drill stems

where N is in blows per ft (0.3 m) and t_{12} is in inch-lb.

(4) The correlation between the CPT and the HPT is sensitive to the grain size characteristics of the soil and can be expressed by the following equation:

$$q_c/t_{12} = 1.09(D_{50})^{0.29}$$

where q_c is in kPax10^{-2}, t_{12} is in in-lb, and D_{50} is in mm.

(5) The HPT can be used for compaction control and would be more practical, convenient, and economical than existing methods.

It also appears, that for compacted soils with similar grain size characteristics general correlations between in place density and HPT torque could be developed.

(6) Since the data presented in this report indicate that the HPT test could be a very useful tool for soil testing and construction quality control, it is recommended to continue this research and obtain additional data, with special emphasis on data in controlled conditions (pressure chamber) and data in soils whose characteristics are well defined. There is also a need for more data for clays and for compacted fills, data on the effect of moisture content on the HPT torque, and data on correlations between th HPT and the vane shear test.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Helical test probes of different sizes, suitable for in situ soil exploration to a shallow (1.8m) depth and compaction control were developed and tested in different soils alongside traditional in situ tests, including Standard Penetration tests (SPT), cone penetration tests (CPT), dilatometer tests (DMT), and in situ density tests. The helical probe test (HPT) is economical and can be performed by a single person. The torque necessary to insert the probe is used as a measure of soil characteristics. It was found that: the HPT test correlates well with the SPT test and the correlation is not sensitive to the soil type (particle size); the HPT test correlates well with the CPT test, but the correlation is sensitive to the soil type; the HPT/SPT and HPT/CPT correlations are consistent with existing data on SPT/CPT correlations; The HPT torque provides a sensitive measure of relative compaction and in situ dry density of compacted soils.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Construction supervision; field test equipment; helical augers; in situ measurements; penetration tests; residual soils; soil investigation; soil mechanics; test procedure.

13. AVAILABILITY

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